NASA/GSFC GROUND SEGMENT UPGRADES FOR KA-BAND SUPPORT TO NEAR-EARTH SPACECRAFT

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1. Introduction

The National Aeronautics and Space Administration's (NASA) Space Network (SN) currently provides communications support at S-band and Ku-band to a variety of low-Earth orbiting science spacecraft via Tracking and Data Relay Satellite System (TDRSS) spacecraft, and ground assets located at the White Sands Complex (WSC). Similarly, NASA's Ground Network (GN) provides communications support at S-band and X-band to science spacecraft via direct links to ground stations located worldwide. NASA's forecasts for science mission requirements reflect the need for data rates up to 1.0 Gbps and beyond. These escalating data throughput requirements cannot be supported by the SN and GN using the present Ku-band and X-band spectrum, respectively. Additionally, NASA's allocations for the TDRSS Ku-band forward and return links are secondary through the International Telecommunications Union (ITU). There will likely be increasing interference to the TDRSS forward links from fixed satellite service Earth stations transmitting in the Earth-to-space direction. In recognition of these constraints, the World Radio Conference (WRC-97) allocated the 25.5 – 27.0 GHz band to the Earth Exploration Satellite Service (EESS) for space-to-Earth transmissions [1]. NASA has procured three next generation TDRSS spacecraft that incorporate a 650 MHz-wide Ka-band Single Access Return (KaSAR) service using a space-to-space link (SSL) in the 25.25 – 27.5 GHz band. As of February 2002, the first of the three new TDRSS spacecraft is now in orbit and fully operational. Once the ground segment infrastructure is in place within NASA's SN and GN to support wide-band communications, future low-Earth orbiting missions will be afforded the flexibility of transmitting high rate data at Ka-band directly to a ground station or through a TDRSS spacecraft.

This paper presents NASA Goddard Space Flight Center (GSFC) activities relating to the implementation of ground segment enhancements within the SN and GN for the provision of wide-band communications services at Ka-band for low-Earth missions. Under the Ka-band Transition Project (KaTP) ground segment infrastructure upgrades are being implemented through extensive use of commercial off-the-shelf (COTS) components as a means to minimize cost. The KaTP is divided into three principle activities. The first activity is implementing modifications to the existing WSC TDRSS ground stations to enable 650 MHz-wide KaSAR service via the next generation TDRSS spacecraft (TDRS H, I, J). One significant feature of this modification is the implementation of the Space Network Interoperability Panel (SNIP) return link frequency plan to facilitate SN cross-support with international missions at Ka-Band.

The second activity is the implementation of a Ka-band demonstration ground terminal at NASA's Wallops Flight Facility (WFF) to support direct-to-ground transmissions. The GN ground terminal was designed to provide an Intermediate Frequency (IF) output that is common with the SN to lower the life cycle cost of NASA's network operations, and ultimately producing interoperable Ka-band data services across the SN and GN while maximizing transparency to customer interfaces.

Finally, the third activity consists of high data rate demonstrations for both SN and GN. These demonstrations will establish that Ka-band telemetry communication from low-earth orbiting spacecraft is feasible at data rates up to 600 Mbps using both the GN and the SN, by assessing the Ka-band link performance via measurements of implementation loss and signal spectra.

2. Drivers for Ka-Band Operations

NASA's SN currently provides communications support at S-band and Ku-band to a variety of flight projects via a TDRS, and ground assets located at the WSC. Similarly, NASA's GN provides communications support at S-band and X-band to flight projects via direct links to ground stations located worldwide. NASA's forecasts for Earth Exploration-Satellite (EES) mission requirements reflect the need for data rates up to 1.0 Gbps, necessitating bandwidths as high as 800 MHz. These escalating spacecraft data throughput requirements cannot be supported by the GN using the present X-band spectrum. Additionally, NASA's allocations for the TDRSS Ku-band forward and return links are secondary through the National Telecommunications and Information Agency (NTIA) and ITU. Therefore, it is likely that interference will increase to the TDRSS Ku-band forward links from Fixed Satellite Service Earth stations transmitting in the Earth-to-space direction. As a result, NTIA and the Department of Defense (DoD) have urged NASA to vacate the Ku-band currently used for TDRSS space-to-space links.

A primary allocation from the NTIA and ITU exists in the 26 GHz band for both Inter-Satellite Service (ISS) and EES service as shown in Table 1. NASA's TDRS H,I,J spacecraft will support Ka-band forward and return links in the ISS allocation. These links offer frequency agility (i.e., forward link is tunable in 5 MHz steps within a 1 GHz band, return link is tunable in 25 MHz steps within a 2.25 GHz band); and the return link bandwidth of 650 MHz can support customer data rates of 800 Mbps or higher. Also, because of the overlap of the ISS and EESS Ka-band allocations (25.5 to 27.0 GHz), low-earth orbit spacecraft can be designed to downlink data either directly to a ground station or through a TDRS H,I,J spacecraft [2]. This provides customers with additional flexibility for both normal operations and contingencies. Other advantages of Ka-band include narrower beamwidths, which reduces the susceptibility to interference, reduced size and mass of the customer spacecraft hardware (especially the antenna), and a higher antenna G/T and system Effective Isotropic Radiated Power (EIRP) than the current TDRSS Ku- and S-band links.

Table 1. Ka-Band Spectrum Allocations Available to NASA/GSFC Missions

Band	Ground Network		Space Network	
	Link/Frequency	Allocated Service	Link/Frequency	Allocated Service
Ka-Band	**Earth-to-Space (Uplink)/** No allocation	**No Allocation**	**Space-to-Space (Forward Link)/** 22.55 – 23.55 GHz	**Primary**: Inter-Satellite
	Space-to-Earth (Downlink)/ 25.5 – 27.0 GHz	**Primary**: Earth Exploration-Satellite	**Space-to-Space (Return Link)/** 25.25 – 27.5 GHz	**Primary**: Inter-Satellite

3. Ka-Band Transition Project Overview

The KaTP is a NASA/GSFC technology development, integration, and demonstration initiative to facilitate the transition of high data rate SN and GN customer spacecraft to the NASA-allocated Ka-band frequencies. NASA/GSFC's approach for demonstrating the SN and GN Ka-band capabilities is to leverage in-house technology development and utilize commercial equipment vendors to provide products that operate within the NASA allocated Ka-band frequencies.

The net result of this project will be wide-band telemetry services that use a common Intermediate Frequency (IF) within the SN and GN. The project will use the common SN/GN IF to perform high data rate demonstrations in conjunction with test receivers and transmitters to demonstrate support of Ka-Band low Earth Orbit (LEO) spacecraft at rates up to at least 600 Mbps. The project conducted a system design review in December 2000 and is currently performing hardware acquisition and integration activities. GN acceptance testing and high data rate demonstrations are scheduled for the August 2002 timeframe. The high data rate SN demonstration is presently scheduled for the fall of 2002.

3.1 Space Network Implementation

The SN ground stations at the WSC (New Mexico, USA) are being upgraded to take advantage of the new TDRS H,I,J spacecraft 650 MHz-wide Ka-band space-to-space return link in the 25.25 GHz to 27.5 GHz band. The WSC ground stations are presently capable of supporting Ka-band customers via TDRS H,I,J at data rates up to 300 Mbps. Table 2 lists the key parameters of the SN 650 MHz-wide Ka-band capability to be provided by the KaTP.

A prime and redundant 650 MHz-wide IF service is being implemented at four of the five Space-Ground Link Terminals (SGLTs) by adding new downconverters and waveguide equalizers. The downconverters receive the 650 MHz-wide Ku-band downlink signal from TDRS H,I,J spacecraft and output a 1200 MHz IF signal. The IF signal is fed into an IF switch for routing to a high data rate receiver. An equalizer is used to correct for phase and amplitude distortions that result when wide band signals propagate through long waveguide runs. Figure 1 illustrates a block diagram of the new and modified KaTP hardware within the White Sands Ground Terminal (WSGT) and Second TDRSS Ground Terminal (STGT) at the WSC.

The downconverter added for the 650 MHz-wide Ka-band service is designed to support the Space Networks Interoperability Panel (SNIP) Ka-band return frequency plan. The Ka-band forward and return center frequencies for space-to-space link communications via data relay satellites were developed by the SNIP to promote interoperability among NASA, European Space Agency (ESA), and National Space Development Agency of Japan (NASDA) space networks. As demonstrated in Table 3, the SNIP center frequencies are offset from the nearest TDRS H,I,J center frequency by 5 MHz [3]. However, the 650 MHz channel bandwidth of the TDRS spacecraft will be able to accommodate the entire SNIP signal. The TDRS H,I,J spacecraft are designed to have a tunable return center frequency for the 650 MHz-wide channel ranging from 25.5284 to 27.1784 GHz in 25 MHz steps.

Table 3 also shows that the nearest TDRS H,I,J KaSA return link center frequency for the 225 MHz-wide channel is offset by 3.4 MHz from the SNIP recommended center frequencies. This 3.4 MHz offset is due to the TDRS H,I,J spacecraft design that shares components in the KaSA payload and the KuSA payload. To support both frequency plans, modifications were made to the existing 225 MHz-wide prime and redundant downconverters at WSC. The modification consist of replacing the existing downconverter local oscillator (LO) with a dual LO; one 3.4 MHz offset from the other. This modification is necessary because the tuning range in the ground receivers is not large enough to allow demodulation of the SNIP center frequencies.

All hardware for the KaTP SN upgrades was obtained from commercial vendors and several lessons learned were gleaned through this process. It is important that sufficient time be spent on defining and refining the specified requirements for the hardware both internally within the project and with potential bidders. Open communications with vendors regarding requirements issues before and after the bid process can play a key role in ensuring timely delivery of compliant products. Requirements that are too restrictive or unattainable can result in higher costs, schedule delays, and a limited response from potential bidders. For several of the hardware procurements for the KaTP SN upgrades, NASA was able to work with vendors to resolve requirements issue. However, delivery delays and non-compliant issues with other key hardware items procured for the SN could have been avoided if the necessary precautions were taken.

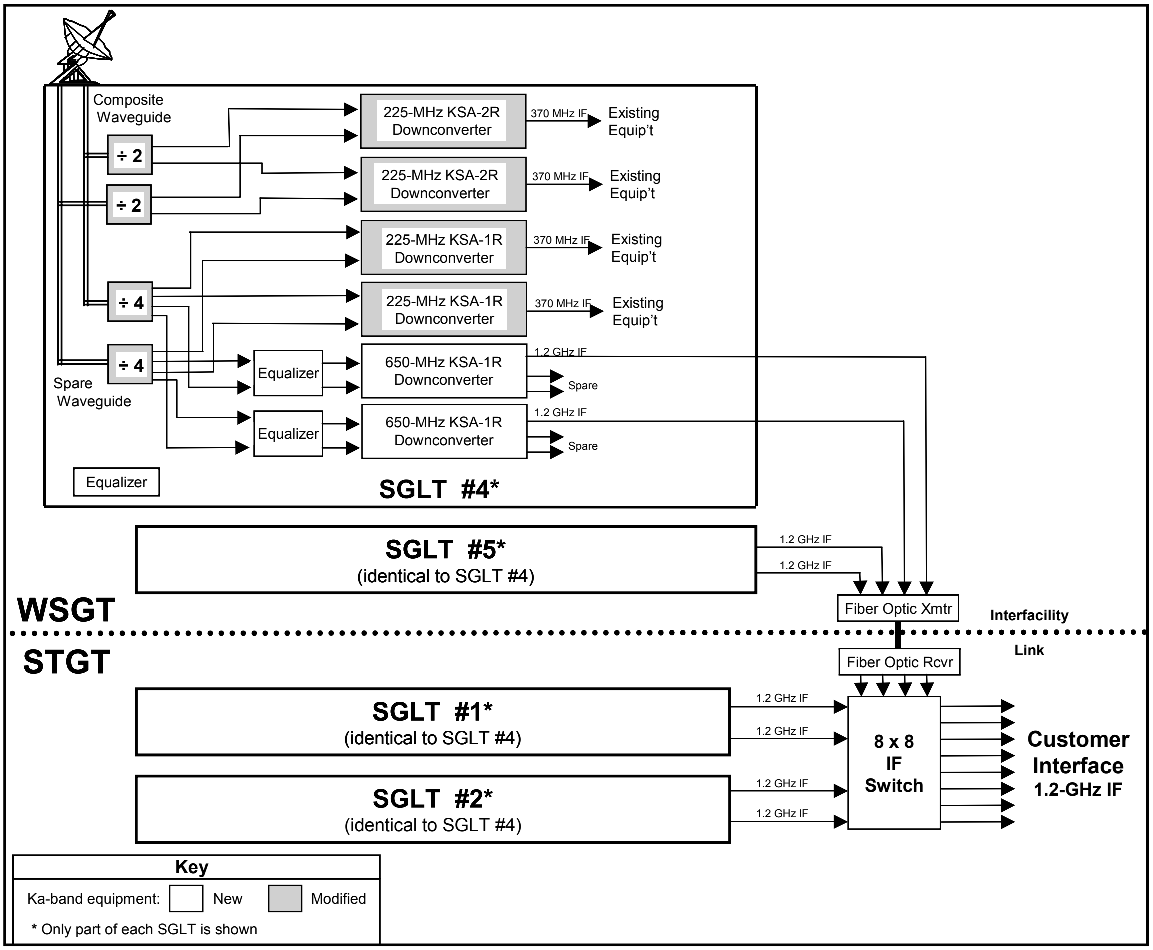

Figure 1. KaTP SN Ground Station Architecture

3.2 Ground Network Implementation

A single GN station will be installed at the NASA/GSFC Wallops Flight Facility (WFF) in Virginia, USA to support unified S-Band command (2025 to 2120 MHz) and telemetry (2200 to 2300 MHz), and Ka-Band telemetry (25.5 to 27.0 GHz). Table 2 lists some of the key parameters of the Ka-band receive system.

The station will consist of 5.4 meter X-Y mount antenna housed in radome with a Ka-band cassegrain feed and an S-band prime focus feed. The Ka-band ground station equipment will provide an IF output at 1200 MHz with an interface identical to the SN Ka-band IF output. The station will support simultaneous Ka-Band and S-band telemetry receive, S-band command transmit, and S-band and Ka-band antenna autotrack. Currently, the ground station will be used only for demonstration purposes, and therefore, will not be fully automated and centrally scheduled for service similar to the exiting operational GN stations. Figure 2 is a block diagram of the GN Ka-band ground station.

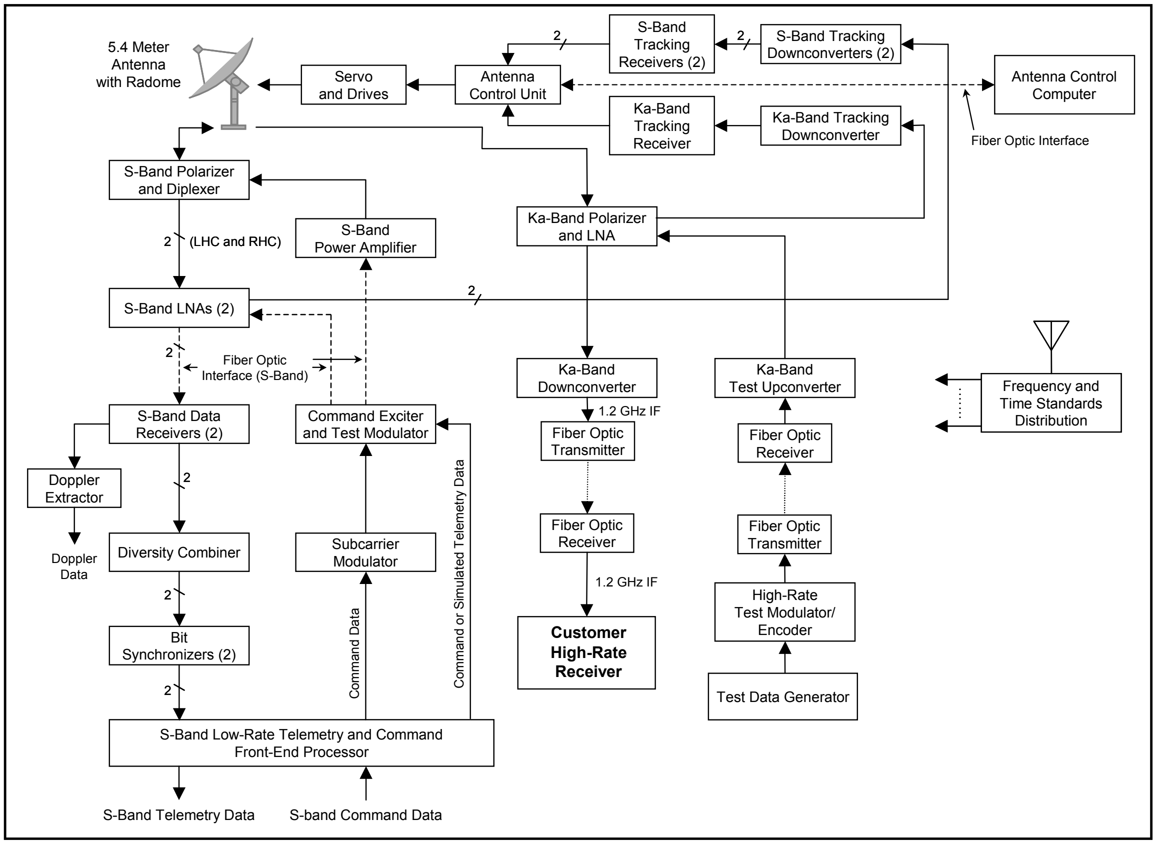

Figure 2. KaTP GN Ground Station Architecture

3.3 High Data Rate Demonstration

The KaTP high data rate demonstration will utilize the new equipment implemented within the SN and the new ground station implemented within the GN to demonstrate the networks' capability to support LEO spacecraft with data rates of at least 600 Mbps. The same receiver will meet the demonstration requirements for both the SN and GN links due to the common IF interface design in both networks. The main objectives of the KaTP demonstration are to:

1. Characterize the performance of the physical return links at rates of at least 600 Mbps
   a. GN: Direct-to-earth Ka-band downlink
   b. SN: return Ka-band link relayed via TDRS H
2. Characterize the acquisition and tracking performance of the GN Ka-band antenna
3. Assess the effects of hardware distortion on the overall link
4. Characterize the GN and SN system designs
5. Provide an end-to-end system; i.e., "reference link" or test system, to help characterize new high rate Ka-band hardware.

The demonstration will assess the Radio Frequency (RF) link performance via measurements of bit error rate and the signal spectra. These measurements will be performed at various data rates and simulated spacecraft EIRPs. For the GN, antenna autotrack acquisition of a moving source will also be demonstrated.

Figures 3 and 4 are high-level block diagrams of the SN and GN demonstration configurations, respectively. A high-rate data transmitter will provide the Ka-band signal source for the demonstration.

The SN demonstration will use the TDRS H spacecraft to relay the signal to an SGLT at the WSC. The SN demonstrations will utilize on-site test equipment including the existing Ka-band Single Access (KaSA) Test Antenna System used to simulate a high rate Ka-band Single Access Return (KaSAR) customer. The GN will use a boresite antenna in conjunction with a high rate signal source for bit error rate testing, and a NASA aircraft will be used for antenna acquisition and tracking tests. The KaTP project will also investigate the use of potential targets of opportunity such as the ENVIronmental SATellite (ENVISAT) spacecraft for the Ka-band demonstrations.

Table 2. Key Ka-Band Parameters for SN and GN

Parameter	SN Requirement	GN Requirement
1. Frequency Range	25.25 to 27.5 GHz	25.5 to 27.0 GHz
2. Antenna G/T	26.5 dB/K, TDRS autotrack mode	32.5 dB/K; clear sky, 10° elevation
3. Axial Ratio	1.0 dB maximum	2.0 dB maximum
4. Polarization	RHC or LHC; selectable	RHC or LHC; selectable
5. Radial Tracking Error	N/A	0.05 degrees; 1 sigma
6. RF Channel 3 dB Bandwidth	650 MHz	1200 MHz
7. IF Output Center Frequency	1200 MHz	1200 MHz
8. Tuning Step Size	SNIP Frequency Plan [3]	125 kHz
9. Gain Flatness	≤ 0.9 dB peak-to-peak over ±230 MHz about IF	≤ 2.0 dB peak-to-peak over ±525 MHz about IF
10. Phase Nonlinearity	≤ 30° peak-to-peak over ±230 MHz about IF	≤ 10° peak-to-peak over ±525 MHz about IF

Table3. SNIP Return Center Frequencies and Nearest TDRS H,I,J Center Frequencies

SNIP Ka-Band Center Frequency	TDRS H,I,J 225 MHz Channel Nearest Center Frequency	TDRS H,I,J 650 MHz Channel Nearest Center Frequency
25.60 GHz	25.6034 GHz	25.5950 GHz
25.85 GHz	25.8534 GHz	25.8450 GHz
26.10 GHz	26.1034 GHz	26.0950 GHz
26.35 GHz	26.3534 GHz	26.3450 GHz
26.60 GHz	26.6034 GHz	26.5950 GHz
26.85 GHz	26.8534 GHz	26.8450 GHz
27.10 GHz	27.1034 GHz	27.0950 GHz
27.35 GHz	27.3534 GHz	27.3450 GHz

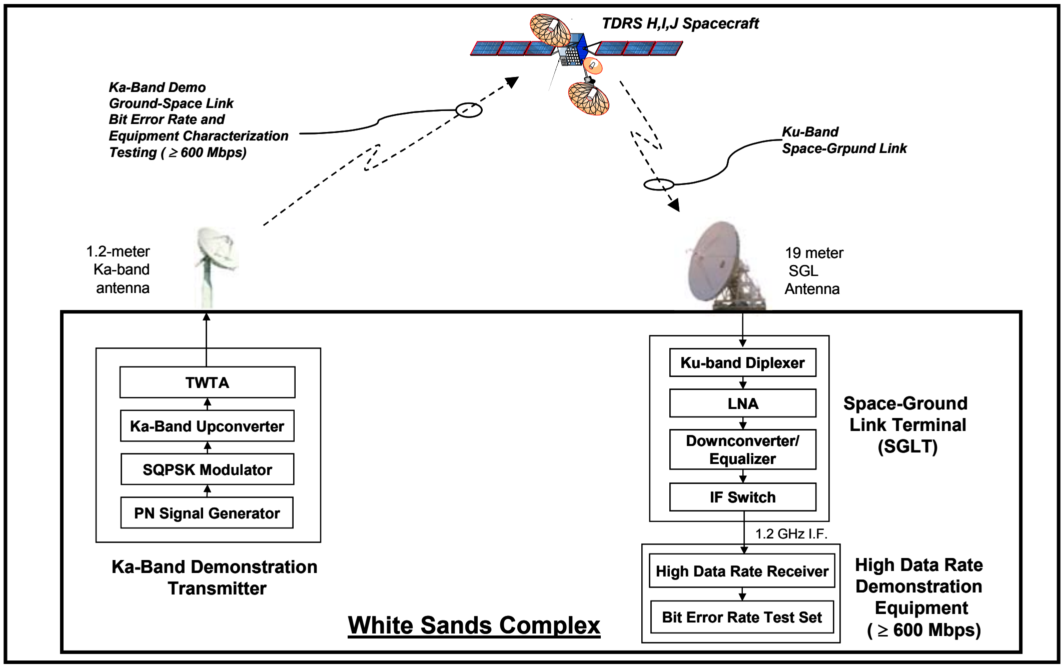

Figure 3. SN Demonstration Configuration

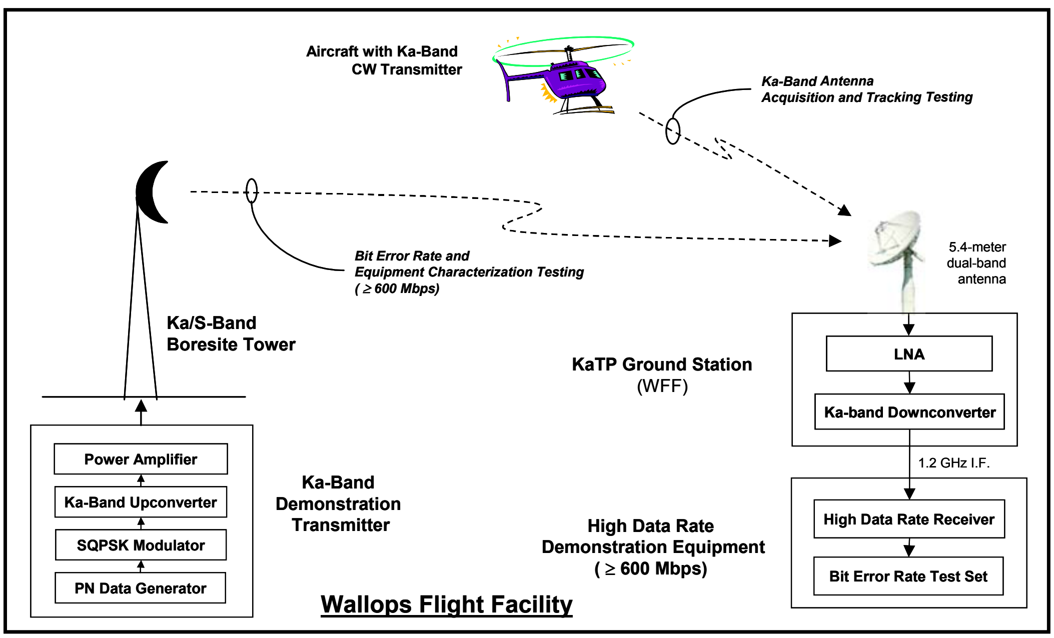

Figure 4. GN Demonstration Configuration

4. Enabling Technology Developments within NASA/GSFC

The planned KaTP high rate demonstration and system performance simulations, combined with the ongoing development and deployment of international commercial and government 30/20 GHz satellite communications systems, illustrate the feasibility of Ka-band operations for future NASA missions. Existing and planned systems such as Iridium, ITALSAT, Astrolink, and Spaceway also support future NASA Ka-band operations by driving the development of communications system components such as

Traveling Wave Tube Amplifiers (TWTAs), solid state power amplifiers (SSPAs), high rate transceivers, wideband filters, and frequency synthesizers/converters. Many of these components are available for future NASA system developers either in their present form as commercial off the shelf (COTS) products, or with minor modifications to operate in the 25.25 – 27.5 GHz EES/ISS allocations.

To further encourage future missions to make the transition from the current S, X, and Ku-band allocations to Ka-band, NASA has developed a comprehensive technology roadmap. The Roadmap addresses the requirements of a wide variety of NASA mission types by identifying multiple alternative Ka-band communications systems architecture concepts. For each architecture concept, the Roadmap identifies the applicable system and component level requirements, assesses the current state of the art in COTS products, and highlights the necessary Ka-band component or subsystem developments.

This section discusses a number of ongoing GSFC technology development activities described in the Technology Roadmap, which promote the utilization of Ka-band by future NASA missions. GSFC sponsored efforts consist of the development of a number of components including:

- The Ka-band Phased Array Antenna
- The 4th Generation TDRSS User Transponder with compatible Ku/Ka Upconverter
- The High Data Rate, Bandwidth Efficient Modulator
- The High Data Rate Parallel Digital Receiver
- Ka-Band SSPA

Ka-band Phased Array Antenna:

The Ka-band Phased Array Antenna was developed for NASA/GSFC by Harris Corporation, (Florida, USA.). A partially populated engineering model antenna was delivered to GSFC in late 2000. The antenna beam steering control, antenna patterns, and gain, were verified using both the GSFC Compact Range Facility and Near Field Range. Additional testing is currently scheduled for mid 2002 with the KaTP GN ground station to determine the effects of the phased array signal distortions on BER performance at data rates up to 600 Mbps. Characteristics of the fully populated antenna are provided in Table 5. [4,5]

Table 5: Ka-band Phased Array Antenna Characteristics

Parameter	Value
1. Frequency Range	25.25 to 27.5 GHz
2. Data Bandwidth	± 400 MHz
3. Scan Range	± 60 degrees
4. Size (mass, volume)	≤ 5.2 kg, ≤ 8.8 x 6.9 x 5.8 (W x H x D) inches
5. Polarization	Left-Hand Circular Polarized, 11 dB Cross-Polarization Isolation
6. Output Power	33 dBW EIRP
7. Power Consumption	< 82 Watts at 2 dB compression point
8. Max Achievable Data Rate (QPSK R1/2)	4 Mbps SN, 310 Mbps GN demonstrated. NASA has started planning for 600 Mbps QPSK tests using the KaTP GN Ground Station.

Fourth Generation TDRSS User Transponder with Ku/Ka-band Upconverter

The Motorola Fourth Generation TDRS User Transponder, when integrated with the GSFC-developed Ku/Ka Upconverter, will provide a low data rate approach for supporting future NASA Ka-band missions utilizing both the SN and the GN.

With the optional Transponder Ku-band module and the GSFC-developed Ku/Ka Upconverter, the 4th Generation User Transponder will support data rates up to 25 Mbps BPSK. The Transponder DC power drain is 6W for receive only and up to 34W for receive/transmit at 5 W of S-Band RF output power, and 5W maximum for 0dBm Ku-Band exciter output. In part because of its low mass and volume (3.6 kg, 8.0 x 6.3 x 5.5 inches), the 4th Generation TDRS User Transponder has been selected for use at S-Band on a number of existing and future missions including AQUA, AURA, SWIFT, X-38, GP-B, and, Long Duration and Ultra Long Duration Balloon Programs. [6]

High Data Rate Modulator

NASA has recently initiated the development of an architecture, design and prototype for an ultra-high rate, re-programmable, all-digital baseband modulator capable of generating a variety of bandwidth efficient waveforms and modulations for data transmission over various RF channels (X-band, Ka-band, etc.). Scheduled for completion in FY05, the modulator will be based upon Complementary Metal-Oxide-Semiconductor (CMOS) parallel designs that can be cascaded to achieve arbitrarily high sample and symbol rates. The architecture will be capable of generating a number of advanced constant envelope modulations, including Consultative Committee for Space Data Systems (CCSDS) recommended Feher Quadrature Phase Shift Keying (FQPSK), Gaussian Minimum Shift Keying (GMSK), and Trellis Coded Modulation (TCM) 8-PSK and other variations of Quadrature Phase Shift Keying (QPSK). The high rate bandwidth efficient modulator architecture will be developed for an eventual migration to a space qualified design.

NASA has also developed a QPSK Ka-band modulator for the Solar Dynamics Observatory (SDO) mission that operates at data rates up to 300 Mbps and provides an output directly at the space science allocated Ka-band frequencies. NASA/GSFC is currently conducting laboratory testing on an engineering model to characterize the modulator's electrical and BER performance.

Ground Terminal Parallel Digital Receiver

NASA/GSFC is currently developing a digital receiver, capable of supporting data rates in excess of 600 Mbps. The demodulator [7] is implemented as a PC card, with a standard PCI interface for configuration and control. The receiver also features a tunable IF front end, anti-aliasing filters, and high-speed analog-to-digital converters. Demodulation and data detection is performed digitally on the sampled data using high speed Application Specific Integrated Circuits (ASICs). This digital implementation results in a more robust, reliable, low noise design with an anticipated very low replication cost. The current version of the receiver is designed to operate at rates up to 600 Mbps and supports Binary Phase Shift Keying (BPSK), QPSK, Staggered QPSK (SQPSK), and Unbalanced QPSK (UQPSK) modulation formats. The next generation High Rate Parallel Digital Receiver will increase the maximum data rate up to 1.2 Gbps and will add support for higher order bandwidth efficient modulations [such as 8-ary Phase Shift Keying (8-PSK) and 16-ary Quadrature Amplitude Modulation (16-QAM)] by using a programmable matched detection filter. The current (600Mbps) version of this receiver will be used for the high data rate SN and GN demonstrations described in Section 3.3 of this paper

Ka-Band SSPA

NASA and Morgan State University (MSU) are conducting a joint team effort to develop Solid State Power Amplifiers (SSPAs) at X-band and Ka-band. The SSPAs will utilize wide band gap semiconductors such as SiC, SiGe or GaN. MSU is currently investigating the DC and RF characteristics of SiC, SiGe and GaN semiconductor devices which they will use to develop a neural network model for the SSPAs that use those devices. A proof-of-concept Monolithic Microwave Integrated circuit (MMIC) amplifier at X-band will be developed and tested using the neural network model of these devices. The X-band test data and the neural network model will be extrapolated to Ka-band to assess its performance for Ka-band application. A Ka-band MMIC SSPA will be developed, fabricated and tested in about 2004 timeframe.

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